Description

THERMOMECHANICAL PROCESSING ROUTES IN COMPACT STRIP PRODUCTION OF HIGH-STRENGTH LOW-ALLOY STEEL

Cross Reference to Related Applications

[0001] This application claims priority from co-pending provisional patent application serial number 60/458,153, filed March 27, 2003, the entire contents of which are hereby incorporated by reference.

Background of Invention

[0002] The present invention relates to the field of high-strength low-alloy steel, and more particularly to methods of thermomechanical processing for making high-strength low-alloy steel that is thin slab cast.

[0003] Conventional thick slab casting is performed in an integrated plant, where steel is made from pig iron and scrap metal in a Basic Oxygen Furnace. Thin slab casting is an

improvement over conventional thick slab casting, is performed in a Compact Strip Production (CSP) plant, and may use metal melted in an Electric Arc Furnace. Both thick and thin slab casting may be done as continuous casting processes. Thin slabs are cast in thicknesses generally ranging from 25 to 100 mm, while thick slabs are generally from 200 to 300 mm.

[0004] Both thick and thin slab continuous casting generally involve the steps of tapping the furnace into a ladle, continuing to heat the steel in the ladle and possibly in a Ladle Metallurgy Furnace where vacuum degassing may occur and alloys are added to create the desired chemical composition. Steel is transferred from the ladle to a tundish from which the steel flows through a water-cooled mold. The steel begins to solidify by forming a shell as it passes through the mold.

[0005] Rolls downstream of the mold work with gravity to control and guide the steel strand through the mold. Thin slab casting eliminates an entire stage of processing, the roughing hot rolling, that is applied to thick slabs. In general, after cooling and solidifying both thick and thin slabs are heated to attain the proper thermal and metallurgical conditions prior to hot rolling under controlled conditions.

After rolling, the temperature of the steel may be reduced by a combination of air cooling and water spray cooling. A combination of controlled rolling and accelerated cooling may be performed that is referred to as thermomechanical controlled processing, and such processing may be used to attain desired characteristics and microstructure in the steel. The rolled steel is then coiled.

[0006] In an integrated mill, slabs of freshly solidified steel are very slowly cooled to room temperature after continuous casting. The low carbon, low alloy hypoperitectic steels experience the following phase transformations during solidification and cooling: Liquid to (Delta Ferrite + Liquid) to (Delta Ferrite + Austenite) to Austenite to (Austenite + Ferrite) to (Ferrite + Carbide). Each of these phase transformations that occurs during cooling leads to a refinement of the grain structure. During subsequent heating, the steel experiences the following phase transformations: (Ferrite + Carbide) to (Ferrite + Austenite) to Austenite. Again, each of these phase transformations that occurs during heating leads to a refinement of the grain structure. Because of the numerous phase transformations that occur during cooling and then reheating, the austenite that forms in a cold charged and reheated slab will be

rather fine, having benefited from the phase transformations. Hence, a thick slab has a fairly refined austenite grain structure by the time it enters the soaking zone in the slab reheating furnace after cold charging in an integrated plant.

[0007] Looking in more detail at rolling processes, in conventional thick slab casting in an integrated plant, hot strip mill rolling generally begins with a 200-300 mm thick continuously cast slab that is cold charged into a reheating furnace and heated to 1200-1300°C. The slab is soaked several hours until a uniform temperature is achieved and the proper metallurgical conditions are obtained. The austenite phase forms from the room temperature ferrite-carbide microconstituent microstructure during the heating portion of the slab reheating process, and this austenite grain structure coarsens during the soaking period. A uniform austenite grain size of approximately 200-400 μm is typically obtained after slab reheating. Then the thick slab is hot rolled to final gauge in two continuous steps, initial rolling in the roughing mill followed by final rolling in the finishing mill. In the roughing mill, the slab is hot rolled, normally in five to seven passes, from the starting thickness to a transfer bar of thickness

of about 25-35 mm. The grain size is reduced through repeated recrystallization until a final grain size of about 50 μm is reached in the transfer bar. After exiting the roughing mill, the transfer bar travels on a transfer table to the entry of the finishing mill. In the finishing mill the transfer bar is hot rolled to the final gauge of approximately 3-12 mm in five to seven passes. The austenite grain structure is further refined in a predictable and uniform way to the equivalent of approximately 20 μm intercept diameter grain size for recrystallized austenite or Sv of 100 mm-1 for pancaked austenite.

[0008] With respect to strain imparted to a thick slab, assuming the thicknesses of 250, 25, and 3 mm, the total rolling reduction imparted in the roughing mill is on the order of 90%, expressed as engineering strain, -2.30, expressed as true reduction strain, or -2.66 expressed as true effective strain. For the finishing mill, the total reduction is on the order of 88%, -2.12 true reduction strain, or -2.45 true effective strain. True reduction strain equals ln(1- true engineering strain). True effective strain for rolling equals 1.155 times true reduction strain. Phase transformations followed by the combination of the roughing mill and the finishing mill allow the integrated plant hot strip to have a

relatively fine austenite grain size. The transformation of this fine grained and uniform austenite on the runout table during air, water spray, and in-coil cooling leads to a fine and relatively uniform final ferritic microstructure. Despite this intensive rolling, there still exist regions of coarse ferrite grains distributed throughout the structure in certain high-strength low-alloy steel grades.

[0009] In a CSP plant, a 50 mm thick continuously cast thin slab, for example, is fed directly, i.e., hot charged, into the finishing hot mill after passing through a thermal equilibrating tunnel furnace typically held at 1100-1150°C. The austenite grain size entering the hot mill in the CSP plant is very much larger (approximately 700 μm) than in an integrated plant (approximately 50μm) because the slab is hot charged into the tunnel furnace and would not experience the multiple phase transformations that occur upon cooling to room temperature then reheating the slab, as found in the cold charging practice used in integrated plants. This CSP slab is hot rolled to final gauge in, for example, six passes in the finishing mill. There is no roughing mill in a CSP plant. An example total reduction in rolling from 50 to 3 mm is 94%, which represents a true reduction strain of -2.81, or a true effective strain of -

3.23. Higher total strains are applied in the five to seven stands of a CSP plant than in the finishing mill of an integrated plant. However, as noted above, the conventional CSP plant hot strip on commencement of hot rolling has a much larger austenite grain size. In many cases, these coarse grains may not be uniformly refined during hot rolling, resulting in a mixture of fine and coarse grains leaving the hot mill and entering the runout table. This mixed austenite grain size often results in mixed coarse plus fine ferrite grains in the final coil. Such a steel may be undesirable, as coarse grains can lower strength and toughness and ultrasonic testing of the steel for checking welds may not be possible because of the high background noise caused by such coarse grains.

[0010] Accordingly, there exists a need for a method of CSP that provides a high-strength low-alloy steel having relatively high toughness and relatively fine and evenly distributed ferrite grains. The steel should allow ultrasonic testing in which there is relatively low background noise.

SUMMARY OF INVENTION

[0011] The present invention is directed to hot rolling of high-strength low-alloy (HSLA) steel cast in Compact Strip Production as a thin slab. The strain and temperature for a

particular steel at initial roll stands where deformation occurs may allow full recrystallization and at latest stands where deformation occurs may not allow recrystallization. Deformation may be absent in the region of strain and temperature where partial recrystallization would occur. The time allowed between deformation at passes through roll stands may be increased by eliminating deformation at one or more central stands that conventionally may be used to apply strain to the thin slab. Eliminating deformation in the partial recrystallization region may allow increased recrystallization over conventional CSP casting, which may result in a relatively fine and uniform austenite grain size that may allow accurate ultrasonic testing of welds.

[0012] In accordance with several embodiments of the present invention, a thermomechanical process for hot rolling high-strength low-alloy steel made by compact strip production into a thin slab is provided. In accordance with one embodiment, the thermomechanical process includes deforming the thin slab at least at one roll stand in the full recrystallization region of austenite in the steel, and next deforming the thin slab at least at one roll stand in the region below the recrystallization stop temperature of the

austenite in the steel.

[0013] In accordance with another embodiment of the present invention, the thermomechanical process includes deforming the thin slab at from two to four initial roll stands with at least approximately -1.39 cumulative true reduction strain in the full recrystallization region of austenite in the steel. Adequate time is allowed to pass to permit static recrystallization prior to additional deformation. The thin slab is deformed at up to four final roll stands in the region below the recrystallization stop temperature of the austenite in the steel.

[0014] In accordance with another embodiment of the present invention, the thermomechanical process includes rolling thin slab cast steel through initial, central, and final roll stands. The thin slab is deformed only at the initial roll stand or roll stands in the full recrystallization region of austenite in the steel and at the final roll stand or roll stands in the region below the recrystallization stop temperature of the austenite in the steel, omitting deformation at least at one selected central strand.

[0015] In accordance with another embodiment of the present invention, a deformation process for hot rolling high-strength low-alloy steel made by compact strip product

into a thin slab is provided. The deformation process consists of deforming the thin slab in the full recrystallization region of austenite in the steel, and subsequently deforming the thin slab in the region below the recrystallization stop temperature of the austenite in the steel.

[0016] In accordance with another embodiment of the present invention, a thermomechanical process for making high-strength low-alloy steel by compact strip production is provided. The process includes adding at least one microalloying element to a molten steel. The molten steel is continuously cast as a thin slab with an approximate thickness of from 25 mm to 100 mm, and the thin slab is thermally equilibrated to a temperature suitable for hot rolling in the full recrystallization region of austenite in the steel. The thin slab is deformed at from two to four initial roll stands with at least approximately -1.39 cumulative true reduction strain in the full recrystallization region of the austenite in the steel. Adequate time is allowed to pass to permit static recrystallization prior to additional deformation. The thin slab is deformed at up to four final roll stands in the region below the recrystallization stop temperature of the austenite in the steel.

[0017] Features and advantages of the present invention will be-

come more apparent in light of the following detailed description of some embodiments thereof, as illustrated in the accompanying figures. As will be realized, the invention is capable of modifications in various respects, all without departing from the invention. Accordingly, the drawings and the description are to be regarded as illustrative in nature, and not as restrictive.

Brief Description of Drawings

[0018] FIG. 1 is a schematic elevation view of a typical Compact Strip Production line for use in an embodiment of the present invention.

[0019] FIG. 2 is a graph of recrystallization stop temperatures as a function of temperature for various alloying elements (by others).

[0020] FIG. 3 is a recrystallization map showing the general relationship between temperature, strain, and recrystallization.

[0021] FIG. 4 is a recrystallization map for a conventional CSP rolling process.

[0022] FIG. 5 is a recrystallization map for a CSP rolling process embodiment according to the present invention.

[0023] FIG. 6 is a recrystallization map for another CSP rolling process embodiment according to the present invention.

[0024] FIGS. 7 and 8 are microphotographs of conventionally hot rolled thin slab cast steel.

[0025] FIGS. 9 and 10 are microphotographs of thin slab cast steel hot rolled in accordance with an embodiment of the present invention.

[0026] FIG. 11 is a graph of Charpy V-notch impact testing for conventional steel and steel produced from trials of embodiments of the present invention.

DETAILED DESCRIPTION

[0027] The present invention is directed to a process for manufacturing high-strength low-alloy steel that is substantially ferritic, has a relatively uniform and fine ferrite grain size, has relatively high toughness, and has relatively low ultrasonic test background levels. The steel is generally appropriate for use as line pipe to the extent that is satisfies certain industry standards, such as, for example, American Petroleum Institute Standards for linepipe and other high performance steel grades. The steel includes one or more microalloying elements, such as niobium, vanadium, titanium, or a combination thereof.

[0028] The metallurgical situation is very different in a CSP plant than in an integrated mill. Referring now to the drawings, FIG. 1 shows a thin-slab casting line 30 used in the

present invention. The casting apparatus includes a mold 32 that receives molten steel 34 from a delivery system 36 filled by a ladle 38. The molten steel 34 passes through the mold 32, which has cooled plates that cause the molten steel 34 to solidify on the surfaces, forming a skin that contains the strand 40 of solidifying steel. The strand 40 is guided by pinch rollers 42 and then completes solidification for its entire thickness. The strand 40 then travels through a reheat tunnel furnace 50 in preparation for the hot-mill 52, where the strand 40 is rolled as it passes through multiple roll stands 54, shown as stands F1 through F6. Additional stands may also be added sequentially or fewer stands may be used; CSP plant hot strip mills most often have from five to seven stands. The strand 40 then cools on a runout table 56, where it is subject to accelerated cooling, and is subsequently coiled by a coiler 58.

[0029] In a CSP plant, therefore, the slab goes directly from the caster to the tunnel furnace to the finishing rolling mill, without the metallurgical benefit of passing through the transformations that occur upon cooling and heating. Hence, the austenite going into the finishing mill of a CSP plant has an austenite grain size of between 600 and 800

μm, which is clearly very much larger than that found in similar products made by the integrated route.

[0030] A problem faced in CSP plants is the difficulty found in producing a uniform, fine grained austenite in the five to seven finishing passes of a hot strip mill from the very coarse grained 600-800μm austenite that enters the finishing mill in a CSP plant. This problem is especially prevalent in the heavier gauges where the total reduction is lower, the strain rate is slower, and the gradients in strain and strain rate are more severe. It is also more prevalent in certain HSLA steels that contain microalloying elements such as niobium (Nb), titanium (Ti), and vanadium (V) that are known to slow down recovery and recrystallization. The steel of the present invention includes at least one microalloying element and has a composition that comprises in percent by weight: $0.01 \leq C \leq 0.20$; $0.5 \leq Mn \leq 3.0$; $0.005 \leq N \leq 0.03$; $0 \leq S \leq 0.1$; $0 \leq Al \leq 2.0$; $0 \leq Si \leq 2.0$; $0 \leq Cr \leq 2.0$; $0 \leq Mo \leq 1.0$; $0 \leq Cu \leq 3.0$; $0 \leq Ni \leq 1.5$; $0 \leq B \leq 0.1$; $0 \leq P \leq 0.5$; and at least one element selected from the group consisting of $0 \leq Nb \leq 0.2$; $0 \leq Ti \leq 0.12$; $0 \leq V \leq 0.15$, with the balance being iron and incidental impurities.

[0031] Heavy gauge strip of HSLA steels, especially those con-

taining Nb, often show arrays of coarse ferrite grains spread throughout the thickness. These are found in strip produced by both integrated and CSP producers. Heavy gauge microalloyed steel strip produced by the CSP process suffers from an additional problem located near the centerline or mid-thickness, where other large, coarse ferrite grains often are found. These grains located throughout the thickness of the strip and especially at the centerline contribute to lower strength and toughness and also cause high background noise in the ultrasonic testing of pipe made from this skelp. This high background level is a problem since it might hide true supercritical flaws or defects.

[0032] The coarse ferrite grains found both throughout the strip and at the centerline of heavy gauge CSP hot strip or skelp are most likely the result of insufficient austenite conditioning experienced during rolling. Coarse ferrite grains result from the transformation of coarse grained or mixed coarse and fine grained austenite. One solution to coarse ferrite grains is to refine the large austenite grains. Refining these large austenite grains is done in accordance with one embodiment of the present invention through the static recrystallization that can occur between passes.

Since the interpass time in conventional strip rolling is rather short, on the order of 0.5-5.5 seconds (generally lower for thinner gauge and higher for thicker gauge), the combination of rapid recrystallization kinetics and longer recrystallization times is desirable to promote complete recrystallization and minimize these large, troublesome austenite grains.

[0033] The kinetics of recrystallization in the interpass period are known to increase with both increased driving force associated with deformation at a given stand and higher interpass temperatures. However, the interpass temperature is not independent but rather is controlled by the pass temperature. This means that for a given rolling schedule the most likely condition for higher interpass temperatures are the early passes, where the stock temperatures are higher than they would be for the later passes. Hence, a tool available for solving this problem is higher driving forces, especially in the early passes such as stands F1 and F2. For a given set of recrystallization kinetics as dictated by the composition of the steel, the austenite grain size and the rolling practice, the extent of recrystallization scales with interpass time; thus, anything that can be done to increase the interpass time would result in more

extensive recrystallization. Therefore, this coarse grain centerline problem in heavy strip produced in CSP plants is addressed in part by the present invention by obtaining higher driving forces for recrystallization in the early passes and increasing the interpass time as compared to conventional processes.

[0034] The driving force for recrystallization is known to increase with higher pass strains, higher strain rates, and lower pass temperatures. Since the initial and final gauges for a given product are set, to drastically increase the pass strain and strain rate requires reducing the number of passes in the strip mill. If, for example, passes F3 and/or F4 are "dummied", i.e., removed or eliminated as actual rolling passes, then the reductions at F1 and F2 can be increased. Under these conditions, at F1 and F2 the reductions will be higher, the strain rates higher, and the bulk of the interpass temperatures relatively higher. These three factors lead to increased recrystallization and the reduction or elimination of the coarse grain austenite in CSP steels. Furthermore, the reductions at final passes F5 and F6 will also be higher, leading to more extensive pancaking of the refined austenite leaving F2. The combination of more recrystallization on leaving F2 and more pan-

caking in F5 and F6 lead to much finer and more uniform ferrite grain structures in the final product. A variety of options is available for dummying roll stands in accordance with the present invention. For example, stands F3, F4, F5, and F6 may be individually dummied. Stands F3 and F4, F4 and F5, and F5 and F6 may be dummied in combination respectively.

[0035] Regardless of which stands are dummied, at the initial stand or stands where deformation occurs the temperature of the steel should be in the full recrystallization region. Then subsequent to the dummied stands, deformation is performed below the recrystallization stop temperature. The period where deformation is eliminated by dummying a stand or stands should be adequate to allow static recrystallization to occur. Recrystallization stop temperatures (RXN) as a function of initial solute concentrations are shown, for example, in the graph of FIG. 2 (source:L.J. Cuddy, "The Effect of Microalloy Concentration on Recrystallization of Austenite During Hot Deformation", Thermomechanical Processing of Microalloyed Austenite (Warrendale, PA: TMS-AIME 1984), 129-140). These temperatures vary with the composition of the steel, and an increase in recrystallization stop temperature occurs with

an increase in the level of microalloy solutes. The steel of FIG. 2 has a composition of 0.07 °C, 1.40 Mn, and 0.25 Si, plus additional alloying elements of Nb, Ti, Al, or V.

[0036] Example thermomechanical processing and recrystallization maps are shown in FIGS. 3-6. FIG. 3 shows the general behavior of austenite during hot rolling. With relatively high temperature and high strain, there is complete austenite recrystallization. Complete austenite recrystallization occurs in the full recrystallization region above Curve A. With lower temperature and strain there is partial recrystallization, which occurs between Curve A and Curve B, Curve B representing the recrystallization stop temperature for any given strain. With still lower temperature and strain there is no recrystallization, as the combination of strain and temperature is in the region below the recrystallization stop temperature, Curve B. The full recrystallization region, partial recrystallization region, and the region below the recrystallization stop temperature are inherent properties of each particular steel.

[0037] FIG. 4 shows a conventional six-pass CSP rolling sequence. This diagram pertains to a certain interpass time, which could be expected to be relatively short, for example, 0.5 to 6 seconds (relatively lower for thinner gauges

and higher for thicker gauges). Pass strains in F1 and F2 may not be above the critical strain, or Curve A, for full recrystallization in the available interpass time. Also, the slab is deformed in the partial recrystallization region at stands F3 and F4.

[0038] Rolling sequence embodiments according to the present invention are shown in FIGS. 5 and 6, where there is no deformation within the partial recrystallization region between Curves A and B, and the combination of heavier pass strain in F1 and F2 plus the longer interpass time leads to more complete recrystallization and subsequent grain refinement. Deformation at F3 and at F3 & F4 is respectively eliminated. Deformation is performed only in the full recrystallization region (stands F1 and F2) above Curve A, and in the region below the recrystallization stop temperature (Curve B; stands F4, F5, and F6 in FIG. 5, and stands F5 and F6 in FIG. 6).

[0039] In addition to being referred to by number (e.g. F1, F2, F3, etc.), roll stands may be referred to herein by their "in service," or not dummied, order. For example, if stands F1 and F2 are in service, F3 is dummied, and F4 is in service, F1 and F2 may be referred to as the first and second roll stands, and F4 may be referred to as the third roll stand.

If stands F1 and F2 are in service, F3 and F4 are dummied, and F5 is in service, F1 and F2 may be referred to as the first and second roll stands, and F5 may be referred to as the third roll stand. Such a convention may be followed for all in service roll stands, based on disregarding dummied stands.

[0040] The figures and tables herein reflect examples of specific embodiments of the present invention, and should be understood as not limiting to its scope. As previously discussed, when a stand is dummied, it may be considered to be eliminated from the rolling sequence, as it does not appreciably deform or imparts only minimal strain upon the strip. Examples of the conventional six-pass integrated and CSP reduction schedules and gauges, and similar data for a four-pass reduction schedule of the present invention, are shown in Table 1.

[0041]

TABLE 1

Pass no.	Integrated Mill		CSP-Conventional		CSP-Present Invention	
	Entry Gauge (mm)	Reduction (%)	Entry Gauge (mm)	Reduction (%)	Entry Gauge (mm)	Reduction (%)
Roughing Mill:						
"Scale Breaker"	235					
R1	188	22				
R2	145	26				
R3	96	41				
R4	62	44				
R5	43	37				
		30				
Finish Mill:						
F1	32.15		54.10		54.10	
F2	17.78	59	27.05	50	21.64	60
F3	10.3	55	16.76	38	11.05	49
F4	6.64	49	11.79	30	11.05	0
F5	4.66	35	8.74	26	11.05	0
F6	3.72	22	7.19	18	8.10	27
Exit	3.22	14	6.17	14	6.53	19

[0042] Table 2 shows data for two conventional CSP rolling sequences, one rolling sequence according to the present invention where one stand is dummied, and two runs where two stands are dummied. It is desirable according to the present invention to maximize the total strain in the early passes while at the same time maximizing the interpass time in the interval where no deformation occurs after the early passes. For example, where stands F3 or F3 & F4 are dummied, the total strain in passes F1 and F2 may be maximized while at the same time maximizing the interpass time between stands F2 & F4 or F2 & F5 respectively. In conventional trials A and B, all six stands deform

the steel, and the time from F2 exit to F3 entry is 1.5 seconds. Trial C has eliminated deformation at stand F3. There the time from F2 exit to entry of the next stand, F4, is 2.5 seconds. Trial D, with stands F3 & F4 dummied, has a time of 4.2 seconds between exit of F2 and entry of the next stand, F5. Trial E has a time of 4.9 for a similar omission of stands F3 & F4. In Trials C, D, and E the interpass times across dummied stands exceeds the time between the prior stands.

[0043]

TABLE 2

Trial A - All Stands in Service	F1	F2	F3	F4	F5	F6
Entry Thickness (mm)	54.10	27.05	16.77	11.79	8.74	7.19
Exit Thickness (mm)	27.05	16.77	11.79	8.74	7.19	6.16
% Reduction	50%	38%	30%	26%	18%	14%
Enter Speed (m/min)	35	52	72	94	118	139
Exit Speed (m/min)	52	72	94	118	139	159
time in between stands (sec)	2.09	1.52	1.17	0.93	0.79	---
Temperature (°C)	1014	987	956	925	896	869
Time F2 exit to F3 entry (sec)	1.52					
F1+F2 true reduction strain	-1.17					
F5+F6 true reduction strain	-0.35					

Trial B - All Stands in Service	F1	F2	F3	F4	F5	F6
Entry Thickness (mm)	54.10	29.22	16.95	13.08	9.72	7.85
Exit Thickness (mm)	29.22	16.95	13.08	9.72	7.85	6.52
% Reduction	46%	42%	23%	26%	19%	17%
Enter Speed (m/min)	34	50	71	87	110	131
Exit Speed (m/min)	50	71	87	110	131	153
time in between stands (sec)	2.19	1.54	1.26	1.00	0.84	---
Temperature (°C)	1011	985	958	931	903	878
Time F2 exit to F3 entry (sec)	1.54					
F1+F2 true reduction strain	-1.16					
F5+F6 true reduction strain	-0.40					

Trial C - F3 Dummied	F1	F2	F3	F4	F5	F6
Entry Thickness (mm)	54.10	25.97	13.50	13.50	9.82	7.74
Exit Thickness (mm)	25.97	13.50	13.50	9.82	7.74	6.52
% Reduction	52%	48%	0%	27%	21%	16%
Enter Speed (m/min)	39	59	87	87	111	135
Exit Speed (m/min)	59	87	87	111	135	156
time in between stands (sec)	1.86	1.26	1.26	0.99	0.81	---
Temperature (°C)	999	974	948	926	897	868
Time F2 exit to F4 entry (sec)	2.51					
F1+F2 true reduction strain	-1.39					
F5+F6 true reduction strain	-0.41					

[0044]

TABLE 2 continued

Trial D - F3 & F4 Dummied	F1	F2	F3	F4	F5	F6
Entry Thickness (mm)	54.10	21.64	11.04	11.04	11.04	8.10
Exit Thickness (mm)	21.64	11.04	11.04	11.04	8.10	6.52
% Reduction	60%	49%	0%	0%	27%	20%
Enter Speed (m/min)	33	53	79	79	79	100
Exit Speed (m/min)	53	79	79	79	100	119
time in between stands (sec)	2.08	1.40	1.40	1.40	1.10	---
Temperature (°C)	975	953	929	910	891	866
Time F2 exit to F5 entry (sec)	4.19					
F1+F2 true reduction strain	-1.59					
F5+F6 true reduction strain	-0.53					

Trial E - F3 & F4 Dummied	F1	F2	F3	F4	F5	F6
Entry Thickness (mm)	54.10	24.89	11.95	11.95	11.95	8.87
Exit Thickness (mm)	24.89	11.95	11.95	11.95	8.87	6.55
% Reduction	54%	52%	0%	0%	26%	26%
Enter Speed (m/min)	29	44	67	67	67	85
Exit Speed (m/min)	44	67	67	67	85	107
time in between stands (sec)	2.48	1.63	1.63	1.63	1.30	---
Temperature (°C)	971	944	919	902	886	860
Time F2 exit to F5 entry (sec)	4.90					
F1+F2 true reduction strain	-1.51					
F5+F6 true reduction strain	-0.60					

[0045] The increase in time between exit of stand F2 to entry of the next stand to deform the strip allows additional time for static recrystallization to occur. This in turn may result in a finer and more uniform austenite grain size. Further,

the higher deformation at the initial stands may serve to increase recrystallization kinetics. The temperature entering F1 is lower than for the conventional rolling sequences, and may be the result of the slower speed at the downstream stands.

[0046] It is instructive to note and compare the sum of the F1 & F2 and F5 & F6 pass strains in Table 2. The sum of the true reduction strains in F1 and F2 are about -1.17 for conventional six-pass rolling, -1.39 for five passes, and over -1.5 for four passes. Dummying one or two passes has a great effect on the pass strains in F1, F2, or F1 & F2. An increase of about 30% in the sum of the F1 & F2 pass strains results for dummying two passes when compared to the standard six-pass sequence shown in Table 3. Similarly, the sum of the true reduction strains in stands F5 and F6 are about -0.37 for six stand rolling but about -0.56 for four stand rolling. This represents about a 51% increase in the total true reduction strain in passes F5 & F6 for the four-pass schedule. Furthermore, the act of dummying one or two passes would also lead to slightly longer interpass times. As indicated above, this would lead to more complete recrystallization of the austenite, especially after the first two passes.

[0047] In general, where F3 or F4 are dummied, the deformation at roll stands F1 and F2 may each be at least approximately -0.60, expressed in true reduction strain. Cumulatively the strain at F1 and F2, or at all stands preceding the dummied stands, may be at least approximately -1.39, expressed in true reduction strain.

[0048] The process of the present invention may also result in finer and more uniform microstructures than conventional CSP processes, and may reduce or eliminate the troublesome coarse-grained ferrite near the centerline. Microstructures of the conventional six stand CSP rolling of niobium bearing HSLA steels are shown in FIGS. 7 and 8. The steel of FIGS. 7 and 8 demonstrates the heterogeneous nature of the grain structure and the horizontally oriented coarse grained banded structure present especially near the centerline.

[0049] Microstructures observed after the four-pass rolling schedule of one embodiment of the present invention are shown in FIGS. 9 and 10. An improvement of the microstructure at the centerline was observed. The very homogeneous ferrite microstructures found after the rolling practice used may be observed throughout the thickness and differ from steel of a conventional rolling practice es-

pecially near the centerline. The steel of FIGS. 9 and 10 was made with stands F3 and F4 dummied, and lack bands of coarse grained ferrite that appear in FIGS. 7 and 8.

[0050] The rolling practice of the present invention and the consequent grain refinement and homogenization may lead to improved mechanical properties over conventionally rolled CSP steel, to include strength and toughness. An example of the improvement in tensile and hardness properties is shown in Table 3. In this trial, the mechanical invention, where one stand was dummied. The composition of Nb-4 comprised in percent by weight: C = 0.045; Mn = 0.50; N = 0.009 (90 ppm maximum); and Nb = 0.025. The composition of Nb-5 comprised in percent by weight: C = 0.055; Mn = 1.10; N = 0.009 (90 ppm maximum); and Nb = 0.045. As shown, mechanical properties for steel, including the Brinell hardness number (HRB), rolled according to the present invention with five-pass rolling were superior to those from the conventional six-pass CSP schedule.

[0051]

TABLE 3

Steel	Rolling Practice	Yield MPa	Yield ksi	Tensile MPa	Tensile ksi	% Elong	HRB
HSLA-Nb-4	6 pass	356	52	442	64	36	79
HSLA-Nb-4	5 pass	420	61	508	74	34	82
HSLA-Nb-5	6 pass	402	58	485	70	33	82
HSLA-Nb-5	5 pass	456	66	547	79	32	87

[0052] The Charpy V-notch impact toughness was also improved with rolling in accordance with the present invention. In the subject embodiments, the conventional six-pass sequence was again compared to either a five-pass or a four-pass sequence. HSLA steel according to the present invention may be produced with the intent to meet or exceed the requirements of American Petroleum Institute (API) Specification 5L for line pipe once the steel is fabricated into line pipe. The results are shown in Figure 11 for two trials of 12.7 mm (0.500 inch) thick steel produced to meet the requirements of API-5L X52 line pipe. In API 5L only yield strength, tensile strength, and elongation are specified, and any toughness requirements are stipulated by the buyer. Minimum characteristics of API 5L X52 are as follows: 358 MPa (52 ksi) yield strength; 455 MPa (66 ksi) tensile strength; and 27% elongation (as determined by formula specified in API 5L). The CVN properties, especially low temperature toughness, were slightly improved when one pass was dummied and the improvement was

even greater when two passes were dummied. The 60 J (50 ft-lb) ductile to brittle transition temperature for the one dummied stand rolling pass is approximately -40°C (-40F), while the two dummied stand rolling pass has a 60 J (50 ft-lb) ductile to brittle transition temperature less than -62°C (-80F). A standard CSP Thermomechanical Processing (TMP) rolling pass with no stands dummied would have a 60 J (50 ft-lb) ductile to brittle transition temperature of around -23°C (-10F) to -18°C (0F).

[0053] Finally, the present invention rolling practice and the consequent grain refinement and homogenization may lead to the reduction in background intensity in the Ultrasonic Testing of final pipe to acceptable levels.

[0054] Although the invention has been shown and described with respect to a best mode embodiment and other embodiments thereof, it should be understood by those skilled in the art that various changes, omissions, and additions may be made to the form and detail of the disclosed embodiments without departing from the spirit and scope of the invention, as recited in the following claims.

[0055] What is claimed is: